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Timing and Radius Considerations for Maintaining Connectivity QoS

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Abstract—Given the potential scale on which a Wireless Sensor Network (WSN) can be deployed, multi-hop communication will be a pivotal component of the system. When redundant nodes are deployed, which are hibernated opportunistically to conserve energy, it is crucial that sub-graphs of the network are not disconnected by the hibernation of a node. In order to ensure connectivity is preserved for all nodes in the area, a protocol is required that oversees routing integrity is maintained. Since this routing topology must be present at all times, this set represents the minimum number of nodes that must be active at any given time for a functioning network. In this paper, the performance of such a protocol is evaluated, in terms of message delivery and node lifetime for various timing and radius parameters. The selection of these, control the potential energy conserved by the nodes through the hibernation process, which can increase operational longevity. In addition, the radius governs the networks resilience to expired nodes, while timing parameters manage the responsiveness of the topology to failed and exhausted sensors. In this paper, we demonstrate the trade-offs that exist when selecting specific values for these variables as well as the impact these have on a number of Quality of Service (QoS) metrics for WSN performance, namely longevity and message delivery.

I. INTRODUCTION

The competence of a Wireless Sensor Network (WSN) is its ability to perform its function in an accurate and timely fashion. These two, related, Quality of Service (QoS) metrics are primarily affected by the density and latency of data from the environment, respectively. Without adequate density, interesting events may not be adequately observed or missed completely by the application, while stale data could result in event detection occurring too late. In opposition to the performance of a WSN is an additional QoS metric - energy consumption. In order to gain the increased resolution of data, additional nodes must be deployed, which increases the aggregate energy consumption of the network.

Alternatively, when redundant nodes are distributed in the region of interest and a virtual soft-deployment is maintained [2], increasing density would result in more *active* nodes. In turn, this increases the average energy consumption per node and reduces overall system lifetime. This relationship gives rise to the Energy-Density-Latency-Accuracy (EDLA) trade-offs for a deployed WSN [5]. Using this suite of properties, en-

sure that increases in the longevity of the network for various protocols are not shown in isolation, and the opportunity cost, in terms of QoS for such an improvement, is also accounted for.

In order to maintain the soft deployment, a protocol is required that opportunistically activates and hibernates nodes with a view to conserving energy. In hibernating a node however, consideration must be given to the connectivity of the remaining active sensors in the topology. Without sufficient connectivity, sub-regions may not be able to forward their data to the appropriate destination, essentially resulting in a blind spot. In this work we examine the performance of such a protocol, in terms of its ability to maintain a connected topology by hibernating and activating appropriate nodes to ensure that as many messages sent are in fact received at the destination. Additionally, we look at the energy cost to the network in ensuring routing integrity is maintained.

In the next section, we look at a theoretical analysis of sensor coverage techniques and how they can be adopted to deliver connectivity within a WSN. We then contrast our work with some related material from the literature, based on the approach to the experimentation, the specific aspects under consideration and the protocols in use. We present the system architecture and the experimental setup in section IV. The results of our experimentation, along with a discussion of their impact for WSN longevity is presented in section V, with conclusions and future work ending this paper.

II. MAINTAINING CONNECTIVITY USING SENSING COVERAGE

While a number of specific strategies have been developed to maintain connectivity in the presence of hibernating nodes, such as SPAN [1], some techniques which can maintain sensing coverage can also maintain connectivity. As proved in [8] and [7], a sensing coverage maintenance protocol can be used to maintain connectivity as long as the following relationship holds:

$$Radius_{transmission} > 2 * Radius_{sensing} \quad (1)$$

A corollary to this is that in order to guarantee connectivity, a sensing coverage maintenance protocol can be used by selecting the sensing radius according to the following formula:

$$Radius_{sensing} = Radius_{transmission}/2 \quad (2)$$

It is this, novel strategy that we adopt in this paper in order to maintain the connectivity of the nodes and we vary the timing and radius parameters of the *sensing* coverage scheme in order to achieve an appropriate QoS. In addition we measure the effect such variations have on the energy consumption, by examining the change in lifetime of the WSN. While techniques specifically designed to manage connectivity have been analysed in the literature, no work to date has examined the connectivity properties of a *sensing* maintenance protocol operating under the constraint of equation 1.

Keypoint: We are not advocating the use of the sensing radius as an accurate model of the sensory modality of the node. The sensing radius is merely a mechanism for controlling overall node density in the sensed area. We are not suggesting that any sensory modality of a node can be varied in such a way i.e. that the sensing radius can be increased or decreased. This abstraction is merely convenient for controlling global node density in a distributed manner based on local information only.

When connectivity is not automatically guaranteed by the sensing coverage component i.e. when equation 1 does not hold, then both sensing and routing coverage must be maintained independently. The strategy defined here can also be employed in this case using two instances of the same protocol. The first instance maintains the desired density using the sensing radius while the second instance is provided with a sensing range of half the transmission radius. A node may now hibernate if, and only if, both protocols deem it to be redundant. If the node is asleep and deliberating about whether to activate, then it must do so if either instance deems it to be critical. In this work we adopt the state-of-the-art Coverage Configuration Protocol (CCP) [7] for our experimentation.

A. Timing Considerations

In order to achieve its goal, the protocol must impose a timing regime on the sensors, in terms of sleep and active times. With a large sleep time selected for the nodes, connectivity holes can appear in the topology that are not promptly filled, due to the long hibernation of candidate nodes, such a scenario can result in disconnected portions of the topology. It is this QoS we are interested in examining for this work, as it is the primary concern for a connectivity maintenance protocol. On the other hand, a long sleep time would conserve considerable energy for the nodes and potentially increase the operational lifetime of the network. With a short sleep time, however, the topology of the network can be very dynamic, which can be problematic for routing messages and may result in undelivered messages. In addition, the shorter the time nodes are allowed to sleep, the less energy can be conserved in the network.

B. Radius Considerations

A second approach is available to tune the performance of a connectivity maintenance protocol, by controlling the density of active nodes through an appropriate radius value. By conservatively specifying the transmission radius for a node, a denser than necessary topology is produced leading to increased redundancy and an ability to cope better with failed nodes. This is at the expense of the additional energy consumed by the nodes that remain awake. Alternatively, overstating the transmission range of a node could potentially lead to disconnected portions of the network, but with the potential benefit of increased network lifetime. In keeping with the EDLA approach, we examine the effect of these parameters, timing and radius, on both the message delivery capability of the resulting topology and the energy consumption within the network.

III. RELATED WORK

A significant amount of literature is available on the main topics of this work, namely, latency, energy, connectivity and message delivery of a WSN. However, none of the material outlined in this section has examined the specific trade-offs that exists between longevity and connectivity for various timing and radius parameters. Additionally, no work to date has explored the connectivity properties of a sensing coverage protocol operating both in keeping with equation 1 and in violation of it.

The work most similar to this is [1], where the authors analyse the performance of a specific connectivity maintenance protocol, SPAN. The authors demonstrate the effect of increased data traffic on the packet loss rate and the variation in power usage per node as the node density increases. No indication is given, however, as to how the delivery ratio of SPAN varies as the density increases and how this impacts the longevity of the network. This is in part due to the fact that SPAN is similar to a clustering algorithm in that it elects co-ordinator nodes within radio range of each other to form a connected backbone. Therefore, as the density increases with a fixed transmission range a constant number of co-ordinations remain active.

IV. EXPERIMENTAL SETUP

In order to evaluate the connectivity of the network, a number of protocols are required on each node. Firstly, the MAC layer is responsible for transmission across the physical wireless channel to a neighbouring node, it will mediate the use of the channel and retransmit failed packets if necessary. In our experimentation, we have selected the 802.11 MAC layer that comes as standard with J-Sim [6], which is our simulation environment.

The next component of the stack will govern the hibernation and activation of the node according to the CCP protocol. The multi-hop communication protocol resides above the coverage layer, which forwards packets for nodes out of direct transmission range of the base station. In this work, the GPSR [4] implementation for J-Sim has been adopted although since

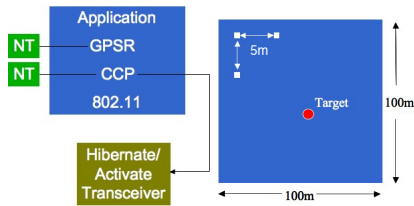


Fig. 1. Protocol stack to maintain a connected network. NT represents the layers neighbour table. Experimental Setup: The deployment has a density of 1 node every 5m. The target is within the environment and the magnitude of the signal received at each sensor is inversely proportional to the distance to the target.

the exact routing protocol is not under consideration here, a number of other choices could have been selected. The final component is the application resident on the nodes. For our purposes, this samples the sensed data at the node and relays it to the base station every ten seconds. The application at the base station may or may not receive these messages and therefore, it can compute the percentage of messages sent from active nodes that are actually received.

The simulated area for this set of experiments is defined as 100 meters x 100 meters with a deployed node density of one node every 5m, figure 1. The result of this is that a fixed density of 400 nodes are used to cover the region of interest. One of the primary reasons for selecting this setup is to allow the results to be generalised to large areas by concatenation of networks similar to this. For example, a 500m x 500m region could be configured using 25 instances of the setup used here in a 5 x 5 grid formation. The transmission range for each node is set at 25m, resulting in a maximum hop count of 6 for the most distant sensors. Simulating a target in the sensed area provides sensory data for the nodes.

In addition to the physical setup, the precise power consumed by the transceiver must also be detailed for the different possible states. In this experimentation it is assumed that transceiver activity will be the single biggest factor in determining the energy consumption of a node and thus its longevity [3]. The values chosen for the power consumption in the different states are based on those used in the experiments of CCP [7]: Transmit power 1.4W, Receive power 1W, Idle power 0.830W, sleeping power 0.130W. Nodes are initially given 100 Joules of energy, which roughly translates to 1/100 of the potential energy for a node powered using current battery technology.

V. RESULTS

Three categories of experimentation are conducted in this section. First the sensing radius is set to a maximum of 12m ($12m * 2 < 25m$) and the performance of the routing maintenance technique is examined as the sleeping and active periods are varied. Energy is measured by the average node lifetime and % of nodes active; Density is varied using the sensing radius chosen to satisfy the radius requirement; Accuracy is the percentage of nodes that are active and whose data reaches the base station. Using this set of metrics, the protocol cannot increase the lifetime of the nodes without

a corresponding effect on the delivery of messages. Since a range of values satisfy the radius requirement, the effect of altering radius and timer values independently are then examined. The performance of the routing maintenance technique is then examined when the radius constraint is violated. The results presented here are the averages of 5 individual executions of the simulation setup.

$$A. 2 * R_{sense} = R_{transmission}$$

From figure 2, the strategy of maximising the active and sleep times to ensure packet delivery can also be seen. However, after an activity period of 40 seconds almost all the trends are decreasing in delivery until the point at which nearly all nodes are active at 100 seconds. The last crest for the three longer sleep periods occurs at 40 seconds for node activity, but as the sleep period gets shorter, so too does this crest. This indicates that, assuming the active and sleep periods cannot be selected to allow all nodes to be active, an optimal value exists for the sleep period and that this value could be a function of the active period selected.

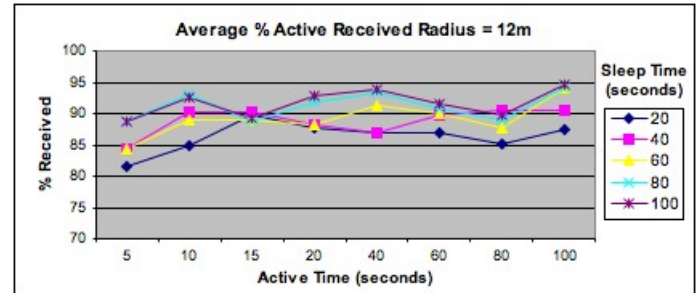


Fig. 2. The effect of the active and sleeping period on the % of active nodes whose messages successfully reach the base station.

The fact that delivery decreases as activity increase beyond a certain point seems to be contradictory to the assertion that the longer the sleeping and activity times, the more stable the topology and therefore the better the routing capabilities of the network. However, as activity increases, with respect to the maximum node lifetime, a greater portion of the network will fail at once and therefore reducing the throughput of the network. A strategy for limiting this effect may be to define the activity periods of the nodes as percentages of the maximum node lifetimes. With an activity period of 60 and a node lifetime 120 seconds, the ratio here is 1:2, alternatively at an activity of 40 seconds, the ratio is 1:3, and the lower ratio performs consistently better across most of the graphs. It may be the case that instead of an optimal activity period, an optimal ratio should be selected in order to maximise routing integrity, however it is left to future work to validate this hypothesis. An additional reason for the downturn in performance could be the link between the activity and CCP beacon periods. Beacons occur once redundancy is evaluated at the end and not during the activity period. By allowing nodes to beacon more frequently neighbouring nodes may get a better picture of the topology and thus improve performance. This will however, impact energy consumption and congestion

and must be evaluated using the EDLA trade-offs to ensure the the QoS is not artificially increased.

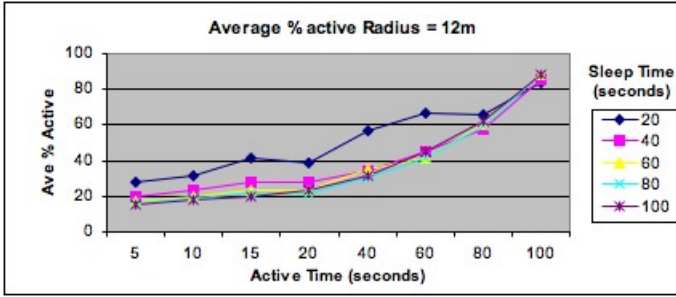


Fig. 3. The effect of the active and sleeping period on the % of active nodes.

The EDLA trade-offs typically operate in opposition to each other, and this is observed here. While the best delivery of packets can be achieved by maximising the active period, this is at the cost of energy consumption through node activity, which affects a nodes lifetime. Figure 3 shows the response of node activity to the parameters. The larger the active period, the more sensors are active at a given time, similarly, the shorter the sleep period the more nodes remain active. This effect is once more mirrored in a nodes' lifetime, figure 4, with the greatest node lifetime existing at the point where the sleep time is maximised and the active time is minimised.

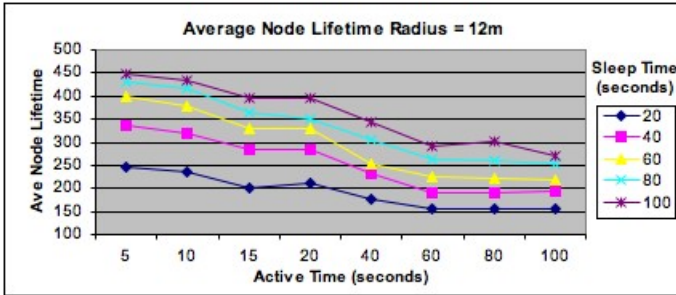


Fig. 4. The effect of the active and sleeping period on the average node lifetime.

In order to select an optimal choice for the timing values, an additional constraint must be taken into consideration. For successful routing of packets, complete coverage is not required, as demonstrated later in section V-C. This means that while the evidence here suggests that maximising sleep time is the best way to achieve packet delivery and longevity in the network, it is not the case for sensing coverage. Packets can be routed around voids in the network, however such voids with respect to the sensing component can degrade application performance. These voids should be filled by hibernating nodes once they activate, however, excessively long sleep periods can allow such holes in coverage to persist for an unacceptable duration.

With this in mind, selecting the timing parameters can be made in a more prudent fashion. For the T_{sleep} variable, the optimal value for both longevity and packet delivery occurs at 100 seconds. However, incorporating the fact that the sensing

component will require a shorter sleep period, this is reduced to 60 seconds. Interestingly, this does not impact on node longevity to a great extent and coupled with careful selection of the T_{active} period this effect can be lessened further. From a longevity perspective activity should be minimised, however, for effective delivery this should be maximised up to an optimal point.

Looking at the trends in figures 2 and 4 an active period of 40 seconds or greater yields no significant change in longevity. An active period of 5 seconds does not deliver enough messages to the base station. Based on this reasoning, an active period of 15 seconds is chosen as it sits in the middle of the remaining possible range of values. Looking at the graphs for an activity period of 15 seconds and a sleep period of 60 seconds would correspond to 88.5% of messages reaching the base station and would give an average node lifetime of 338 seconds on the 100 Joules of energy the nodes are given at the start of the simulation.

B. $2 * R_{sense} \ll R_{transmission}$

Since 12m is not the only radius that satisfies the radius requirement, this set of experiments explore the effect of conservatively selecting the sensing radius in order to maintain connectivity. These conditions represent the typical densities of nodes required to maintain sensing coverage and so demonstrate the effect of timing parameters with high node densities on the connectivity maintenance protocol.

1) *Average % Active Received:* As the radius value decreases, the density of the soft deployment increases leading to a greater proportion of the network being active. With this increased activity however, there is no drop off in messages received, in fact for the increased density there is, in general, a slight increase in the % of messages reaching the base station, figure 5 and figure 6. This would appear to confirm that an increase in density leads to a more reliable routing infrastructure, but potentially at the cost of an increase in latency and energy consumption, which will be explored later in this section.

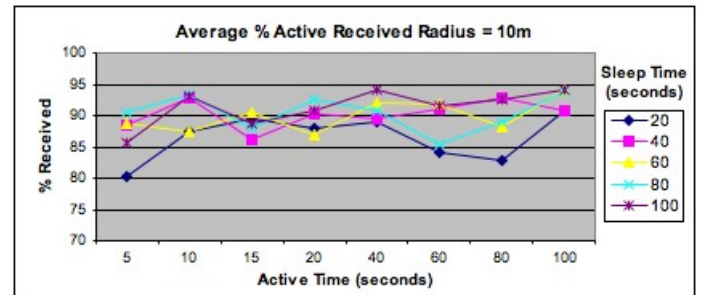


Fig. 5. The effect of the active and sleeping period on the % of active nodes whose messages successfully reach the base station.

2) *Average % Active:* As the radius decreases, the % of the active network increases assuming that the sleeping and active periods are held constant, figure 7 and figure 8. The graphs become less curved as the density increases, indicating that the effect of the active period on node activity reduces as the

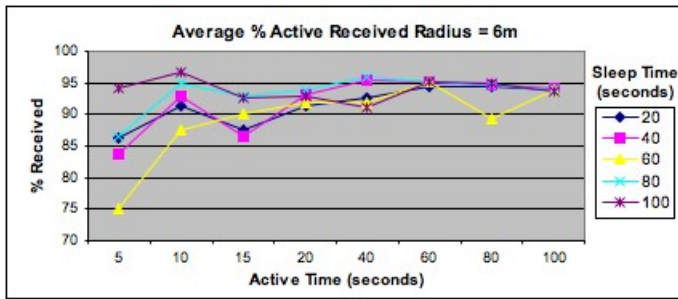


Fig. 6. The effect of the active and sleeping period on the % of active nodes whose messages successfully reach the base station.

density increases. This is due to the fact that less nodes can be considered redundant as the radius decreases. In addition, the effect of the sleeping period is also reduced as the radius decreases, as can be seen by the tight bunching of the curves when the radius is 6m.

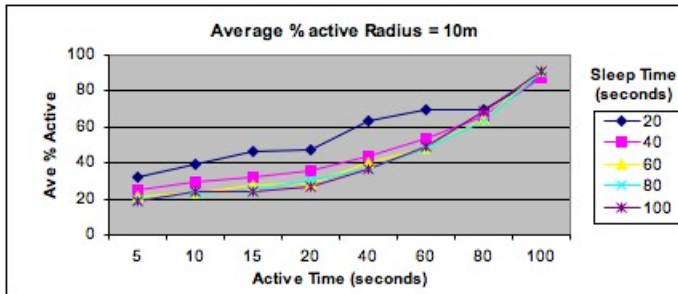


Fig. 7. The effect of the active and sleeping period on the % of active nodes.

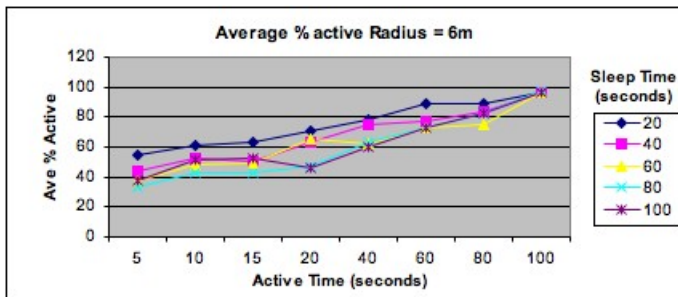


Fig. 8. The effect of the active and sleeping period on the % of active nodes.

3) *Average Node Lifetime*: While the curves still decrease as the active period decreases, the effect is diminished as the radius decreases across figure 9 and figure 10, this can be seen from the progressive flattening of the curves. Likewise the effect of the sleeping period is also diminished as the radius decreases, this is seen from the proximity of the trends in the different graphs. In general all of the trends are reduced as the radius decreases due to more nodes remaining active to maintain coverage.

4) $T_{active} = 15$ & $T_{sleep} = 60$: The results obtained here are not limited to this routing example. Since a sensing radius less than the theoretical maximum of 12m will typically be required to maintain adequate sensing density, it is important to characterise the routing component under such conditions.

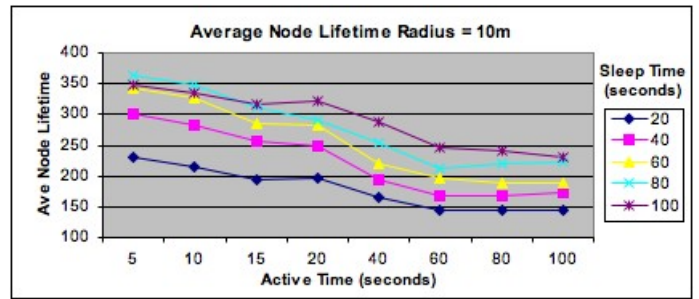


Fig. 9. The effect of the active and sleeping period on the average node lifetime.

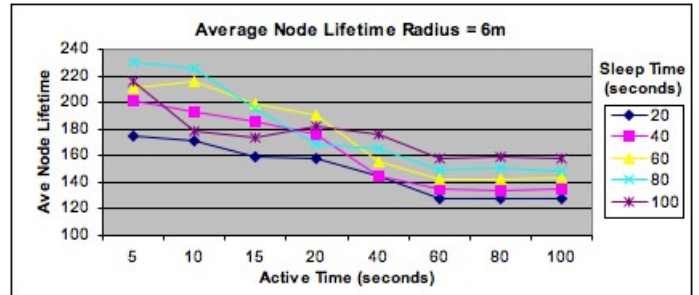


Fig. 10. The effect of the active and sleeping period on the average node lifetime.

This allows experimental results in the future to be examined in more detail, for example in terms of application accuracy given that only a subset of data sent will ever reach the base station. For the specific timing parameters previously selected, active = 15 and sleep = 60, table I demonstrates the change in the metrics as the radius decreases and the density increases. From these results it can be seen that while the average node lifetime drops, due to the increased activity, no decrease in delivery is observed. In fact in relation to the 88.5% received when the radius is 12 metres an improvement can be seen in message delivery. This is partially due to the more stable topology that results as the density approaches the case where all nodes are active all of the time.

C. $2 * R_{sense} \gg R_{transmission}$

In this set of experiments the effect of violating the radius requirement is explored. While mathematical proofs of the requirement are detailed in the literature, the practical implications for violating the relationship are provided here.

1) *Average % Active Received*: When the radius requirement is breached, the characteristic curves are still present in figures 11 and 12, however the delivery performance is reduced across all trends. As the radius increases, the effect of the active period becomes more pronounced, with a more dynamic topology producing considerably worse results. Interestingly, with an active period of 15 seconds and a sleeping period of 60 seconds nearly 83% of the data gets through to the base station when the radius is set at 15m and nearly 70% when the radius is 20m. In addition, for a radius of 20m it appears that the shorter sleep periods are more desirable, due to sparseness of the network and the increased requirement to fill coverage holes quickly. This is a crucial result that

reinforces the decision to reduce the sleep period from 100 to 60 seconds in the previous section.

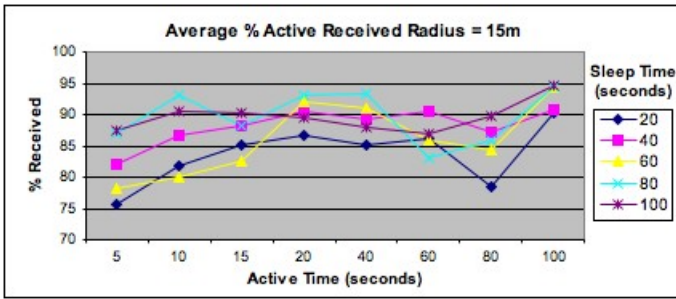


Fig. 11. The effect of the active and sleeping period on the % of active nodes whose messages successfully reach the base station.

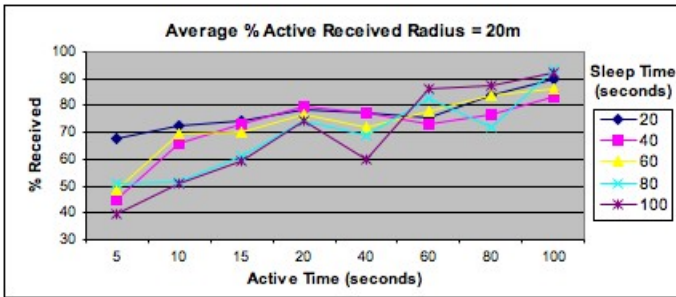


Fig. 12. The effect of the active and sleeping period on the % of active nodes whose messages successfully reach the base station.

There are a number of possible reasons for this performance. Firstly a good multi-hop protocol, like GPSR, can route around coverage holes. Therefore messages will typically reach their destination but may take more hops to do so. A second reason for this performance is through beacon loss. When two nodes beacon at the same time, the receiving node may not get either of them due to interference in the channel. When the node evaluates its redundancy, it may do so without full knowledge of its neighbours, as such, more nodes may stay active than are required by the protocol to ensure connectivity. A more lenient radius value can lead to a reduced density consistent with one produced under perfect radio conditions.

2) *Average % Active*: Once again a similar trend is observed in the activity data as the active period increases, figures 13 and 14. In general, there is a considerable reduction in node activity, particularly for the shorter active periods. The graphs, however, again increase as the active period does, due to all nodes initially starting in the active state. The effect of sleep duration on activity diminishes as the radius increases, after 40 seconds very little change in activity is observed, except for the curve representing a sleep time of 20s.

3) *Average Node Lifetime*: The real benefit to increasing the sensing radius beyond the threshold lies in the dramatic increase in node lifetime, figure 15 and 16. As before, when the active period increases the life span of the node reduces but as the node sleeps for longer its life time increases. When the radius increases further to 20m, the longevity for all points increases. If a sleep period of 60, and an active period of 15

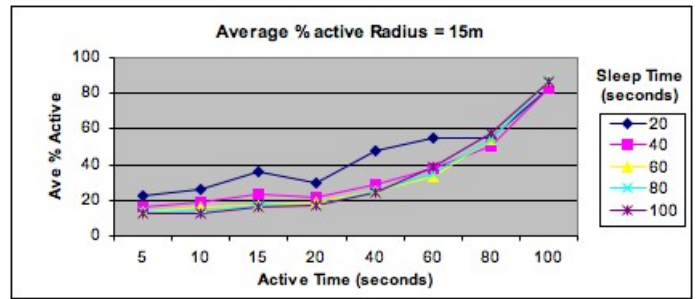


Fig. 13. The effect of the active and sleeping period on the % of active nodes.

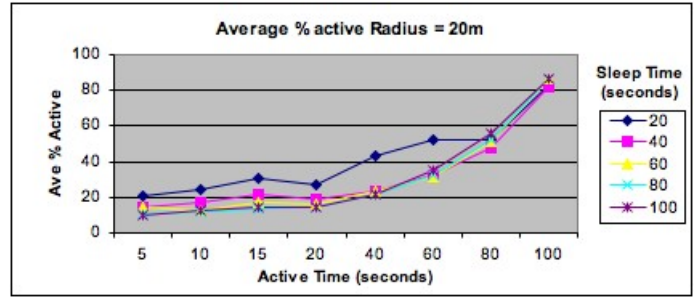


Fig. 14. The effect of the active and sleeping period on the % of active nodes.

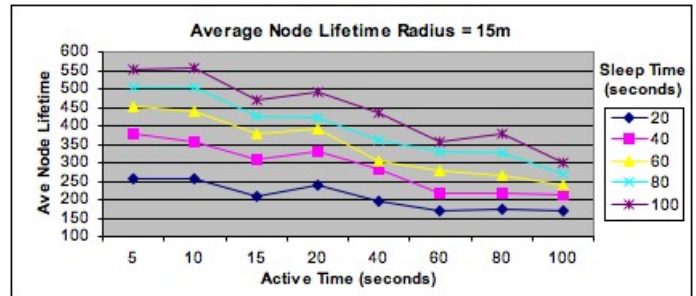


Fig. 15. The effect of the active and sleeping period on the average node lifetime.

seconds is analysed, the longevity increases to 375 and nearly 400 seconds for a radius value of 15m and 20m respectively. Comparing this with the observed 338 seconds when the radius is at 12m, the increase in longevity can be seen and crucially, this can be placed in contrast to the reduction in delivery of messages from previous experiments in table I.

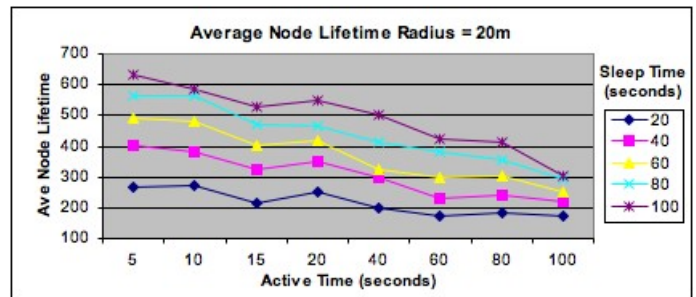


Fig. 16. The effect of the active and sleeping period on the average node lifetime.

The reduction in message delivery, sacrificed for the in-

	r=6	r=10	r=12	r=15	r=20
% active received	90%	90%	88.5%	83%	70%
% active	50%	26%	24%	18%	17%
average lifetime	200s	290s	338s	375s	400s

TABLE I
CHANGE IN % ACTIVE RECEIVED, % ACTIVE AND AVERAGE NODE
LIFETIME AS THE RADIUS INCREASES.

creased longevity, can be seen for the different selections of the radius value. In some cases such reductions may not adversely impact the application, however, the precise effect on application accuracy of violating the radius constraint is left to future work.

VI. CONCLUSIONS

An established regime for prolonging the longevity of a WSN is through the opportunistic hibernation of nodes. Hibernating too many can result in disconnected regions, where no observed data can be acquired through the topology. In order to prevent this, specialised protocols have been designed, which only permit the hibernation of a node if the remaining active sensors will remain connected. Sensing coverage mechanisms can also maintain connectivity as long as the transmission radius is greater than twice the sensing range. In this work, we specifically analyse the connectivity performance of a sensing coverage scheme according to its ability to get the active sensors data to the base station. We also examine the effect that varying timing parameters and sensing radius size has on the QoS and longevity of the network.

A number of conclusions can be drawn from this set of experiments. Firstly, an optimal sleep/active period exists where the two forces of energy saving and response to failed nodes balance, failed nodes introduce coverage holes that need to be plugged by a newly awakened node. The QoS provided by the network can be quite erratic depending on the values of the parameters selected, affecting the temporal operation of message delivery. In general, by choosing a conservative value for the sensing radius, more nodes are activated leading to a reduction in node lifetime but a slight increase in message delivery is observed. It is important to remember that latency of the messages is not considered here.

Violating the established radius requirement does not impact performance to a great extent and can add considerably to node lifetime. Under the EDLA trade-offs no gain is without cost, thus ensuring fair comparison - looking at a radius value that just meets the requirement yields 88.5% received and a node lifetime of 338 seconds when the active period is 15 seconds and the sleep period is 60 seconds. Alternatively for the same timing periods, 70% is received but each node on average would be active for 400 seconds when a radius of 20m is chosen, a considerable increase in longevity. The effect of the timing parameters selected here must be evaluated in relation to application accuracy, and this is left to future work.

ACKNOWLEDGEMENT

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